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APPLICATION OF WIND POWER TO RATIONAL GENERATION OF ELECTRICITY

J. Juuls

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16. Abstract

The history and development of windmills in Denmark and elsewhere is sketched. The costs and problems of generating electricity by steam, water and wind power are compared. Pointing out that the wind is Denmark's only major natural source of power and dividing the application of wind power into an economic and a technological part, the author discusses how the Danish wind could be harnessed to supply power not only in the requisite amounts and at the lowest cost, but also under all circumstances, so as to make Denmark self-sufficient in the matter of energy.

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APPLICATION OF WIND POWER TO RATIONAL GENERATION OF ELECTRICITY

J. Juuls

Events of recent years have shown that it is essential to keep /137*
electric power supply to the public intact, and there is good reason to assume that this will be even truer as electrification is extended and acquires a decisive influence over every aspect of everyday life.

Without light, without radio, partially without telephones and newspapers, not to mention motive power for mills, bakeries, dairies, slaughterhouses and most of agriculture and industry, the wheels of progress would come to a standstill.

It is therefore of vital importance not only that electricity be produced in the requisite quantities at the lowest possible cost, but also that everything be done to ensure the maintenance of electric power supply under all circumstances.

As is well-known, until a few years ago electric power supply in Denmark developed by budding without any overall plan or any governmental control or intervention, until by Law No. 169 of 1935 the Electricity Board was assigned a certain controlling authority, which was of great significance in maintaining electric power supply especially during the war years.

Since the end of the Second World War the result has been that the country is being supplied with electricity from a dozen steam powerhouses and several hundred smaller diesel powerhouses. The operation of these powerhouses is based on imported foreign coal and crude oils, and the maintenance and economics of operations

* Numbers in the margin indicate pagination in the foreign text.

depend on the availability and price of the latter, though during the difficult war years our domestic peat and lignite was partially able to take the place of foreign coal.

Coal and crude oils have not been very stable power sources for Denmark in recent generations, as can be seen from the 1916-1946 price curves of Fig. 1: prices changed by over 1000% and crude oils were totally absent during both wars, which amounts to about 25% of the time.

With the aid of imported coal and domestic fuel it was possible to maintain a more or less continuous electric power supply, even though it was sometimes necessary to introduce rationing, but nobody with any familiarity with the situation will deny that the danger of an electricity shortage has been impending to an alarming extent, and it must almost be regarded as a conjuncture of fortunate circumstances that things have gone as smoothly as they have. /138

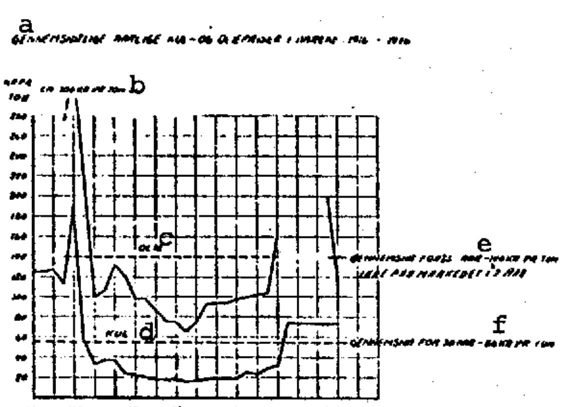

Fig. 1.

Key: a. Average annual coal and oil prices for the years 1916-1946; b. About 100 kr/t; c. Oil; d. Coal; e. Average for 25 years: 140 kr/t, not indicated for 7 years; f. Average for 30 years: 56 kr/t

There are only a few places apart from the coal districts themselves that are as nicely situated for coal supply as Denmark. Our waterways -- partially over rivers and canals, partially over the sea -- to coal districts in Poland, Silesia, the Ruhr and England are not particularly long, so that freight charges from the coal mines to Danish harbors are relatively low, and we have had plenty of opportunity to take advantage of the competition for the coal market among different countries, which has characteristically exemplified itself by the fact that coal prices in, for example, Czechoslovakia and Sweden were as a rule higher than in Denmark, and often enough twice as high, in spite of the fact that these countries are situated closer to local coal districts. The reason for this has been that these countries are obliged for the most part to transport their coal by rail, and the location of these countries has prevented them from exploiting the competition among the competing coal-producing countries. Experience has shown that, whenever war breaks out, oil supply to Denmark practically speaking ceases. Electricity generation based on oil has therefore proved to be not very reliable in times of crisis.

The situation with regard to coal has been different. During both World Wars coal arrived in Denmark the whole time, albeit in insufficient quantities: during the First World War at sharply fluctuating prices, while the prices during the Second World War almost became firmly established at about 300% over the price of coal between the two wars. This, however, does not paint a true picture of the situation because, as is well known, the value of money has also fluctuated sharply, but if we take this circumstance into account, we will find that the price of coal during the last war increased by about 100%, where it has remained up to this day.

It is difficult to predict where coal prices will find their level in the future, but there are indications that coal will not be so cheap as before, in the first place because coal mines in most countries have come under state control, in the second place because the existing and probably continuing labor shortage in most coal-producing countries will be utilized as a lever to improve the miners' lot, which, to be sure, has also been very much needed in most places. In the third place, it is probable that international agreements will prevent competition for the coal market among different countries and, finally, the chemical industry will probably assert itself as a purchaser of coal to a greater extent than hitherto because a great deal of artificial products will be manufactured directly from coal.

These circumstances taken into consideration are surely one of the main reasons for the almost feverish extension of water power plants in those countries which have water power at their disposal, and this phenomenon can be observed not least in those countries which have an abundance of coal mines. Of course Denmark itself has no water power to speak of, but it is feasible to supply Denmark with electricity from our neighboring countries Sweden and Norway, which are relatively well provided with water power, which is why the supplying of electricity from these countries has now been debated for almost a generation. But nothing much has come of it except that Sweden has delivered to us some hydroelectricity, whenever there was a surplus of it in southern Sweden, but in the main this has redounded to the advantage only of a part of Sjaelland, and the amount of electricity that has been transmitted by existing plants constitutes only a small fraction of the entire country's needs.

An extension of plants such that the entire country could be supplied with hydroelectricity from Sweden and Norway would be very expensive, and the associated technological difficulties, although they do not seem to be insurmountable, also afford grounds /139
for a good deal of speculation. Moreover, it must be taken into consideration that such a supply is so vulnerable from the standpoint of reliability, especially under wartime conditions or incident to other social or international upheavals, that it will be necessary for Denmark to make provision for full reserves of electricity supply here at home. That is why the extension of steam power plants, which is partly underway and partly in the planning stage, fits into the Norwegian and Swedish hydroelectricity transmission project.

Atomic power, about which so much has been written of late, may also acquire significance for electricity generation in Denmark.

According to Electrical World of 14 September 1946, the United States Atomic Energy Commision at Oak Ridge, Tennessee, has submitted a report to the United Nations Council, in which it is explained that at existing prices a 75,000 kW atomic power plant will cost 25 million dollars while a comparable heat power plant will cost 10 million dollars, i.e., 335 dollars and 133 dollars per kW, respectively. At a 3% rate of return on the capital investment and with a 100% utilization time electricity from the atomic power plant will cost 8 mills per kW while electricity from the heat power plant will cost 6.5 mills.

The price of coal at plants in the eastern states is currently about 7.5 dollars per ton.

With coal costing 10 dollars per ton, the price will be about the same for both sources of power. The report concludes with the mention that no atomic power plant has yet been built for electricity generation for public use, and that the advantages of an atomic power plant will be especially apparent in regions where no coal, oil or water power is forthcoming. It is further explained that 1 kg of plutonium corresponds to 10,000 kg of coal, which means that the former can be flown in to the consumption center without raising any of the transportation problems that coal does for a steam power plant, for it is difficult to foresee any circumstance that might prevent the necessary plutonium from being flown in. The article does not say anything about the period of amortization that is envisaged and, if we assume the utilization time to be the usual 25-35% (since 100% utilization time is not easy to achieve), the price per kWh will be a good deal higher.

Another possibility for Danish power supply lies concealed in the Danish wind, and it is precisely this possibility that has occasioned the present article.

It so happens that the wind is Denmark's only major natural source of power. It is somewhat changeable and unstable, but on the other hand it is available for a great number of hours in the course of the year in a practically unlimited amount that far exceeds our power requirements.

In earlier times -- indeed, as far back as we can trace our history -- the wind was practically our only motive power for ships and mills, and the Danes excelled as builders of sailing ships and windmills. It was not until the advent of diesel engines and steam turbines that the old Danish windmills were superceded, for with the aid of electricity it became possible to transport power from diesel engine and steam turbine to most places where power was needed, and the power from these sources of energy was stable and always available.

Not inconsiderable are the assets that were scrapped. Until about 25 years ago there were in Denmark about 2500 Dutch windmills and about 20,000 smaller wind engines, which together were able to produce 100-150,000 hp, or just as much as considerably larger high-tension plants. Cheap though the power from existing windmills was, this power was discarded in favor of a more expensive, but more stable power, namely, electricity, which shows that it is not only having cheap power that counts, but also the condition that the power be available in sufficient quantities at all times.

It is not necessary to be a particularly keen observer to have noticed that in recent years a great deal has been taking place in the air and in our ability to harness it from the technological point of view.

Had nobody come up with the idea of designing aircraft wings in a different manner from that employed in designing the blades of the old windmills, things would look pretty different in this world, and examination of Figs. 2 and 3 below will reveal that something has also happened with respect to building windwheels.

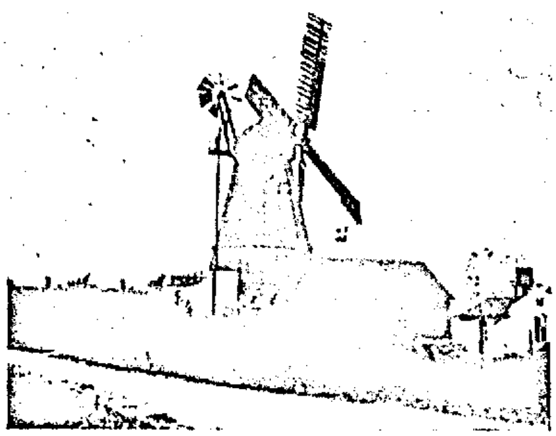

Fig. 2

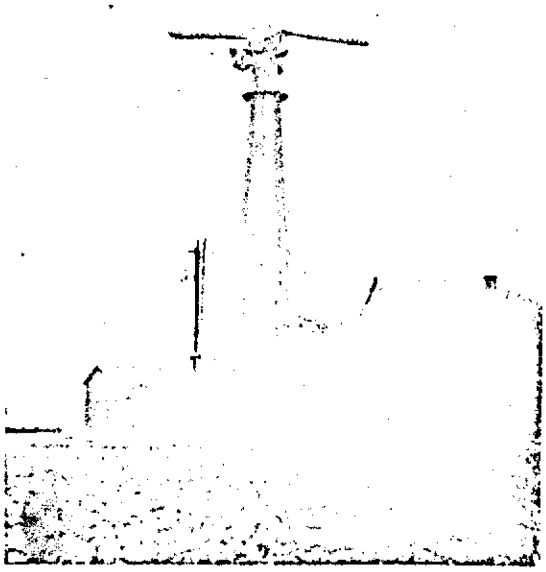

Fig. 3.

Fig. 2 is a 1905 photograph of Professor La Cour's /140
experimental mill and Fig. 3 shows a windmill of recent years; the difference is striking. The latter is able to develop more power than the former. The wheel diameter of La Cour's mill was 22.8 m and the new windmill has a blade span of 18.5 m; and it can be seen that the consumption of construction material is considerably less in the case of the modern windmill.

But the main difference is that on the basis of the experience acquired in designing aircraft we are now in a position to make the ideal blade with a streamlined shape and in agreement with the laws of aerodynamics. Whereas La Cour's windmill had vanes that could not revolve with a greater tip speed than 2.5 times the wind speed, the new windmill revolves with a tip speed of up to 7 times the wind speed. Perhaps it is not so easy to see immediately what an advantage this represents, but the point is that it is not the wind pressure affecting the front of the blades that draws the most, but that the principal factor is the suction that arises at the rear of the blades. So a change for the better has taken place with respect to the exploitation of wind power, and Fig. 4 shows the power that can be obtained by means of different types of windmills. Also clearly to be seen from this figure is the progress that has been made. The question is now whether this progress has been great enough to warrant building wind-driven electric power plants on a large scale to supplement expensive and hard-to-get coal.

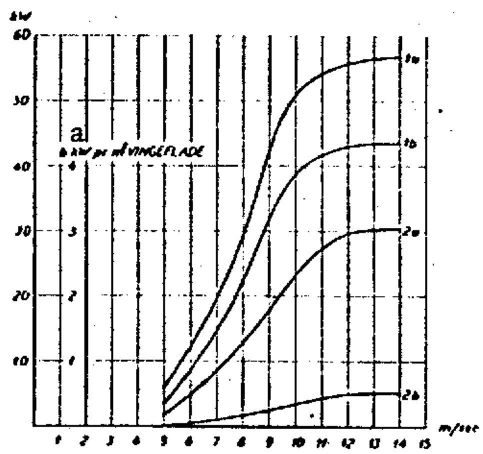

Fig. 4.
Windmill performance. 1a and 1b: two streamlined blades; 18.5 m blade span; about 13 m^2 blade area. 2a and 2b: four blades built like folding sails; 18 m blade span; about 60 m^2 vane area.

Key: a. b: kW per m^2 blade surface

Often during the war years I got to thinking about this involuntarily as I tramped through the mosses of South Sjaelland in the stiff March wind in search of peaty soil for the Masned Island plant; but one thing soon /140
became abundantly clear: in this domain there can be no such improvising as in the production of peat. This we were able to do during the last war, but the next time things won't be so easy, because most places are simply bare of mosses, and our power needs at that time will probably be much greater than now and require such great stores of fuel that their procurement in Denmark will be impossible.

In every country where water power is to be found it has been decided that water power plants must be developed to the greatest

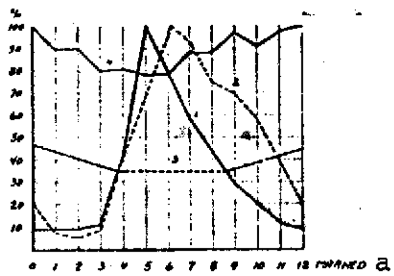

Fig. 5.
1: Discharge in flood from Alps; 2: Discharge in a Norwegian river; 3: Economically justifiable development of water power in Switzerland; 4: Typical curve for Denmark's electricity consumption per month. The hatched part indicates the electricity that must be generated by other motive power than water power.

Key: a. Month

possible extent in spite of the fact that water power, like wind power, is not available all of the time, so that there can be no question of exploiting water power as other than a supplement to another power supply, as a rule steam power plants.

The difference in availability of water power and wind power is that the former oscillates but once a year, whereas wind power oscillates in shorter periods, most often from day to day; but on the average, the wind is present for about just as many hours a year as water power. Curve 4 of Fig. 5 shows how electricity consumption oscillates from month to month throughout the year, and curves 1 and 2 show how water power behaves in a flood from the Alps and in a Norwegian river.

Whence ensues the adverse state of affairs that water power is least available when electricity consumption is greatest and, conversely, most available in the summer, when electricity consumption is least. Any attempt to equalize this state of affairs would require very expensive barrages and the inundation of extensive, as a rule fertile, valleys, which is thus a very expensive proposition.

Curves 1 and 2 of Fig. 6 show what the average wind speed is for 6 and 10 m of wind at Bovbjaerg, Sejro and Gedser. Whence it ensues that the rhythmic availability of wind power keeps pace with electricity consumption, which is an advantage as compared with water power, but it also shows that cooperation between hydroelectric and wind power plants in the course of nature would be an expedient combination. Furthermore, wind power is present in Denmark everywhere that power is needed whereas water power is generally found far from towns and thickly settled regions, so that long and expensive supply mains must be built in order to transmit power to the consumption center.

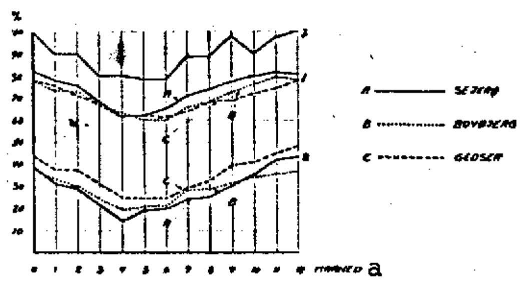

Fig. 6.
1: Wind speed 5-6-7 m/sec and above 1% of the time in different months of the year; 2: Wind speed 5·10-11 m/sec and above; 3: Typical curve for Denmark's electricity consumption per month.
Key: a. Month

The exploitation of water power is therefore an immense task, which is often solved either as a state enterprise or by cooperation between a great number of townships, in view of the consideration that vital social interests are at stake and that the great works that must be carried out lend themselves to regulating the labor market, for which reason the state often finds it expedient to make cheap capital available, in the same manner as we here in Denmark, in the case of different land reclamation projects, road repairs, etc., have implemented measures to regulate the rate of employment and in so doing also achieve values of lasting importance for the public. As far as water power is concerned, there can be no doubt about the correctness of this procedure, and in fact the result has been that colossal projects have been carried out /142
in America, the Soviet Union, Sweden and Norway, as well as Switzerland and other places where such possibilities exist. Everywhere the result has greatly redounded to the advantage of the countries in question.

Now the question is whether it would not be just as legitimate to consider the exploitation of wind power in the same manner as has been the case with regard to water power, and then especially in the case of countries like Denmark, which have an abundance of wind but no water power or coal deposits to speak of.

The application of wind power to large-scale electricity generation can be divided into an economic and a technological part.

With respect to the economic aspect, it is natural to compare the cost of electricity generation by steam and by water power plants here in Denmark, but for heuristic purposes it is also interesting to consider what it costs in general to set up and operate water power plants abroad.

With a view to reliability and reserves, a steam power plant capable of supplying, for example, 50,000 kW will generally be built for 100,000 kW, which today will cost an estimated 450 Kr. per kW with the means that are necessary for distribution of the energy and coordination with other plants. If we assume 4% interest on the capital investment and 20 years' amortization, the yearly payment will be 7.26%, and inasmuch as the utilization time of Danish steam power plants is about 2000 hours a year, the electricity from these plants will cost per kW about as follows:

Interest and repayment on 450 Kr. per kWh at 7.36% =	33.00 Kr.
Coal consumption for production of 2000 kWh = 0.6 × 2000 = 1.2 t of coal at 56 Kr. =	67.20 Kr.
Wages and maintenance = 1 Øre per kWh =	20.00 Kr.
Total	120.20 Kr.

or per kWh 120.20/2000 = 6.0 Øre,

which is accordingly the price of electricity ex plant when the coal price is estimated as the average price for the last 30 years, and it would hardly be reasonable to reckon with a lower coal price in the future.

Furthermore, it must be noted that steam power plants require a relatively great expenditure of foreign currency both for investments and for operations, for which reason investing in such plants is not suitable as a regulating factor for the domestic labor market. So we must not count on the state's making cheap investment funds available for steam power plants.

Before the war, the expansion of water power plants in Germany, Sweden and Norway cost 700-1000 Kr. per expanded kW with mains.

The first expanded plants, however, were the most accessible whereas the plants that are now being expanded require longer supply mains, and inasmuch as prices have risen everywhere, we must assume that the expansion price per kW now hovers about 1500 Kr.

In coming years Norway is planning to expand by 150,000 kW yearly. For this purpose 220 million Kr. have been provided for in the budget, which is accordingly 1460 Kr. per kW.

The annual utilization time of water power plants ranges from 2000 to 6000 hours, but according to Swedish and German statistics it is most often about 4000 hours.

The amortization time for water power plants can be fixed at a longer period than is generally the case for a steam power plant, where boilers and turbines are exposed to high temperatures, with the result that the service life of these parts is relatively short. If we assume an amortization time of 20 years for steam power plants, we can probably assume 30 years for water power plants, and inasmuch as these also require larger earthworks and concrete works, state and township are as a rule interested in the action of workers as a regulating factor on the labor market, for which reason the public often makes cheap funds available for this action of workers.

If we assume an amortization time of 30 years and a 3% interest on invested capital, the costs per kWh for water power will be as follows:

Service of interest and sinking fund of invested capital 1500 Kr. per kWh at 5.1% =		77.50 Kr.
Administration and maintenance 1% of 1500 Kr. =		15.00 Kr.
	Total	92.50 Kr.

If we assume an annual utilization time of 4000 hours, the price will be 92.50/4000 = 2.3 Øre. /143

As compared with this, the situation for wind power is about as follows:

For the modern wind-driven electric power plants built during the war, which are used in Denmark in some direct-current plants, the invested capital is 1000 Kr. per kW and before the war was about 400 Kr. per kW. With rational construction of this type of plant, which is the most advantageous from the economic point of view, we could probably come down to about 800 Kr. per kW. The utilization time for the windmills used in Denmark is, according to statistics, about 2000 hours a year, but is often less, as little as 1000 hours a year and under.

Provided windmills could run both day and night and exploit all the wind power that is present, the utilization time would rise to about 4000 hours, but this is never achieved in the smaller plants, where sufficient accumulators are not available, so that the windmill must be stopped whenever the accumulator is full, and there usually is not so much consumption that the output can go directly into the network.

If now we suppose that a wind power plant has been incorporated into a large-scale high-tension network, then practically all of the windmill's output can be utilized all of the time. Under these circumstances there will be round-the-clock consumption of about 20% of the day's maximum load, and at those times when the now-existing load is slight, surplus wind power can be utilized for heating purposes, which means that coal can be set aside for those times when the wind is calm. In this manner we could probably raise the utilization time of wind power plants to 3000 hours.

If we adopt the same points of view for the exploitation of wind power as for that of water power, we can assume a 3% return on the invested capital.

Experience shows that windmills have a service life of over 30 years, but tending and maintenance must be fixed somewhat higher per kilowatt than for water power plants. If we fix this cost at 1 Øre per kWh, we shall not be far off the track. Annual expenses per kW will then be:

5.1% service of interest and sinking fund of 800 Kr. =	40.80 Kr.
Tending and maintenance 1 Øre per kWh =	30.00 Kr.
Total	70.80 Kr.

For a utilization time of 3000 hours, the price per kWh will be 70.80/3000 = 2.36 Øre, i.e. about the same as for hydroelectricity and less than half of what it costs to generate electricity in steam power plants.

Now this position may meet with the objection that it is necessary to build steam power plants to supplement wind power, and if we must have the first anyhow it is unnecessary and uneconomical to build wind power plants, too. But the same can be said of water power plants: in this case, too, it is necessary to have steam power plants in reserve for those times when the water freezes over in mountains and rivers; but this state of affairs certainly has not prevented us from extending water power plants on a large scale and from continuing to do so at a furious pace.

In what follows we estimate the cost of generating 100 million kWh of electricity by steam power alone and by combining steam and wind power so as to generate, firstly, 30% and, secondly, 70% of the total output by wind power.

We assumed that the generation of 100 million kWh of electricity will give rise to a maximum of 30,000 kW, and that the district heating plant will have full reserves of steam power.

1. Generation of 100 Million kWh of Electricity by Steam Power Alone

/144

60,000 kWh steam power plant	
Invested capital 60,000 × 450 =	27,000,000
Interest to be paid in installments at the rate of 4% for 20 years, annual payment 7.3%	
Service of interest and sinking fund of 27 million at the rate of 7.3% =	1,971,000
Coal consumption 0.6 kg coal per kWh = = 60,000 tons of coal at 56 Kr. =	3,300,000
Administration, staff and maintenance 1 Øre per kWh =	1,000,000
Total Kr.	6,271,000

Price per kWh = 6,271,000.00/1,000,000.00 = 6.271 Øre.

2. Generation of 100 Million kWh of Electricity by Combined Steam and Wind Power, Estimated for 70% Steam Power and 30% Wind Power

Steam power invested capital 60,000 × 450 =	27,000,000
Wind power 10,000 kW at 800 Kr. =	8,000,000
Total invested capital =	35,000,000
Steam power plant interest to be paid in installments at the rate of 4% for 20 years	
Wind power plant interest to be paid in installments at the rate of 3% for 30 years	
Service of interest and sinking fund of 27 million at the rate of 7.3% =	1,971,000
Service of interest and sinking fund of 8 million at 5.1% =	408,000
Production of 700 million kWh at 0.6 kg coal = 42,000 tons at 56 Kr. =	2,352,000
Administration and maintenance of steam power plant as mentioned under point 1	1,000,000
Administration and maintenance of wind power plant 1 Øre per kWh of 30,000,000 =	300,000
	6,031,000

Price per kWh = 6,031,000.00/1,000,000.00 = 6.031 Øre.

3. Generation of 100 Million kWh of Electricity by Combined Steam and Wind Power, Estimated for 70% Wind Power and 30% Steam Power

Steam power plant invested capital 60,000 kW at 450 =	27,000,000

Wind power plant invested capital 25,000 kW at 800 Kr. =	20,000,000
Total invested capital	Kr. 47,000,000
Service of interest and sinking fund of steam power plant for 20 years = 7.3% of 27,000,000 =	1,971,000
Service of interest and sinking fund of wind power plant for 30 years = 5.1% of 20,000,000 =	1,020,000
Production of 30,000,000 kWh at 0.6 kg coal = 18,000 tons at 56 Kr. =	1,008,000
Administration and maintenance of steam power plant as mentioned under point 1 =	1,000,000
Administration and maintenance of wind power plant 1 Øre per kWh =	700,000
Total Kr.	5,699,000

Price per kWh = 5,699,000.00/1,000,000.00 = 5.699 Øre.

From this it follows that exploitation of wind power to the greatest possible extent will mean cheaper electricity, even if we must reckon with the necessity of having steam power plants with full reserves of steam. On the other hand, it would be defensible to argue that wind power can to some extent supplement steam power plants in such a manner that by expanding wind power plants we can cut back somewhat on the building of steam power plants because damage to the latter coinciding with the year's greatest maximum and with a calm is not very likely in the event of steam power plants with such a low utilization as is talked about in this event.

On the assumption that it will always be an advantage to spare foreign currency, political economy is also involved. In order to construct a wind power plant about 150 Kr. per kW is spent on the importation of iron, steel and metal; everything else for the construction of windmills complete with electrical installations is domestic work. This means that for electricity from wind power only about 0.3 Øre per kWh will be spent on imports while for electricity from steam power about 4.5 Øre per kWh will be spent on imports since it is envisaged that about half of the investment for a steam power plant is foreign labor and materials. /145

Today Denmark's electricity consumption is about 1 billion kWh. Producing 80% of this by wind power would therefore mean a saving in imports of about 30 million annually, and inasmuch as electricity consumption increases on the average by about 6% each year, in a few years this amount would be doubled.

The construction of wind-driven electricity generating plants on a large scale can be so carried out that it will be a good regulator of the labor market for many different trades, and by its very nature it is a matter that ought to be encouraged as a land reclamation project, which also opens up the prospect of setting up a domestic industry with exportation possibilities.

The social as well as the economic aspect of the matter has a claim on our attention. How the matter stands from the technological point of view is another question, but Denmark is the country with the greatest experience of the social and economic aspects. Since the time of Professor La Cour about 40 years ago there have been several hundred wind-driven electricity generating plants in operation in Denmark. If these acquired no very great signficance, this is due to the fact that it was in the nature of things for them to be built as small, independent plants relegated to operation with accumulators, which were expensive to run and unable to accumulate very great quantities of energy, so that the windmill wound up with a very poor utilization time. Nowadays things are different. All over the country there are large interconnected supply plants with a great need for electricity.

To these extensive plants windmills would be able to impart their power with a great annual number of utilization hours.

As Professor La Cour terminated his trial of the state's experimental windmill in Askov at the turn of the century and was about to propose a practical method for the exploitation of wind power it happened that the diesel engine appeared on the scene. With the aid of the then-existing cheap crude oil the diesel engine could generate cheaper electricity than wind power plants, for which reason it was the one to be chosen at first as motive power.

If we had known at that time what difficulties we would come up against in procuring the necessary oil, things might have taken a different turn; wind power would certainly have been utilized to a much greater extent.

One might be justified in taking up a skeptical attitude with regard to the adduced examples of electricity production prices, and different points of view can be adopted in the matter, but it is difficult to gainsay the fact that a couple of Øre more or less per kWh is much less important than having the necessary amounts of electricity available under all circumstances. This can best be seen from the fact that in many places electricity has been the object of heavy indirect taxation, and yet it has been able to make progress almost faster than technology has been able to keep up with.

Today Denmark's electricity consumption is about 1 billion kWh. So a difference of 1 Øre in the price represents 10 million Kr. yearly. This is a lot of money, but should electricity not be forthcoming for just one day, many people would lose their earnings. If we assume that the employment of 100,000 workers is directly dependent on the presence of electricity, this alone represents 2 million Kr. daily. This is not counting the inconvenience and waste of time for another 100,000 people, plus losses due to productive machinery coming to a standstill. So it soon becomes very expensive to have a less than reliable electricity supply. Everywhere the need for electricity is about to become so extensive that all possibilities for procuring the needed power are being looked into. Switzerland, where power is lacking at that time of the year when water power gives out, is starting to investigate the possibility of harnessing wind power, and the same can be said of England.

Russia seems to have come a relatively long way. Here windmills were being manufactured on a large scale even before the war. The plan for the Petrovskiy Plants in Cherson was a yearly production of 30,000 windmills with a total power of 160,000 kW. The possibility of building large windmills of up to /146
10,000 kW had been investigated. Such a windmill was planned for Mt. Ai Petri in the Crimea and was supposed to supply current to Yalta, among other places (Fig. 7).

Before this project had gotten underway, a smaller windmill had been built in Balaklava (Fig. 8) as an experimental model. The results of these experiments, however, showed that the consumption of material per unit of power is less for small windmills than for large ones because the tip speeds of the vanes must necessarily be the same for small and large windmills. So the number of revolutions is disproportionately small in the case of large windmills, and the difficulties encountered in making transmissions for the gear wheel and bearing pressures were great, just as the building of the necessary high supporting towers was relatively expensive per unit of power.

The same result seems to have been arrived at in Germany, where it has even been proposed to built 20,000-kW windmills on 500-m high towers.

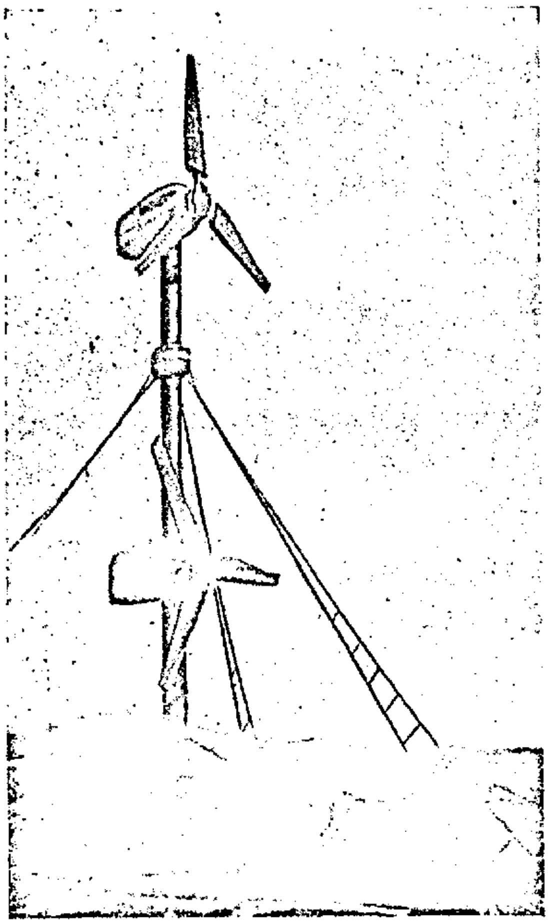

Fig. 7.

A 1000-kW windmill has been operating in America for several years and, according to the latest reports, the experience acquired with this windmill will now be made the basis for building a 10,000-kW windmill with two blades on a common supporting tripod. Other American investigations seem to indicate that a 100-kW windmill results in the least building expenses per kW.

On a continent there is but little wind power at the earth's surface whereas at an altitude of 200-400 m it is abundantly present. So it is possible that large windmills might have a chance here. Things are different in the case of a flat littoral like Denmark; here there is relatively a lot of wind only a few meters above the ground.

So there is no reason for us here in Denmark to think of windmills reaching for the skies in more than one sense. Here in Denmark we will undoubtedly get the cheapest power by using windmills in the 50-100 kW range, i.e., with 18-24 m sails; in /147
other words, the size that a century of experience has shown us must not be exceeded.

The most economical manner for us here in Denmark to harness the power of the wind is therefore to set up a sufficient number of these windmills in the most suitable places, i.e., on the old windmill hills, along open beach or in level country, and thus

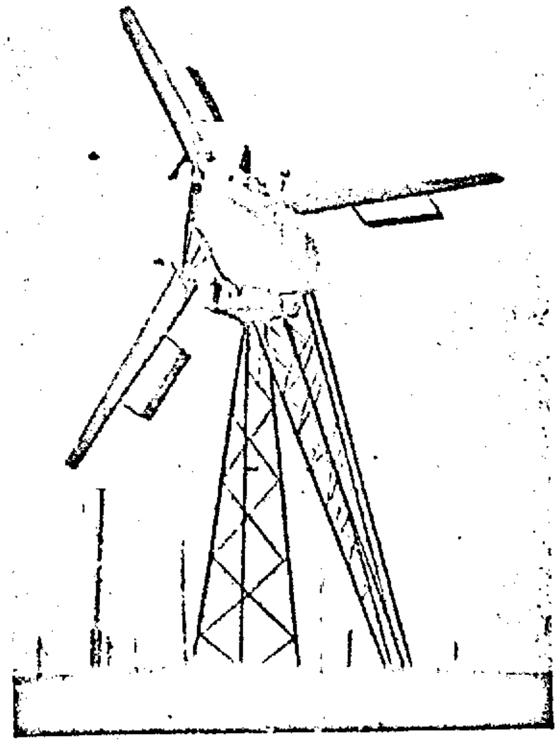

Fig. 8.

let their energy be accumulated in our existing high-tension system, which will thus serve not only as disseminators of energy, but also as accumulators, so that the high-tension system can supply the accumulated energy not only to local consumers, but also to towns and other large-scale consumers.

As far as direct-current windmills are concerned, the technical aspect of the matter was solved in a satisfactory manner in the time of Professor La Cour. In recent years an improvement was introduced into these windmills by using a differential excitation shunt dynamo instead of an ordinary shunt dynamo. With suitable differential excitation we can get the windmill to follow the wind speed in the most advantageous manner.

For producing alternating current we cannot make use of this advantage unless we first generate direct current and then transform it to alternating current. This means high construction costs and a reduction in efficiency of about 25%, as well as the introduction of complications into the windmill.

It turns out, however, that with the aid of an asynchronous motor driven as a generator we can easily produce alternating current directly from the windmill with relatively good efficiency. In this case, the windmill must run with an approximately constant speed from the time it begins to furnish current. When the generator is fully loaded, it must be prevented from being overloaded by means of the windmill's automatic devices. In this manner, if we assume the wind speed indicated in the reports of the Meteorological Institute, we can obtain more than 90% of the amount of electricity that could be obtained if direct current were instead produced with a differential excitation shunt dynamo.

What this relationship looks like can be seen from Fig. 9, which shows a curve adopted from the French engineer Eiffel. This shows what the working capacity of a two-bladed windmill is for different tip speeds in relation to the wind speed. It can be seen that only when the tips of such a windmill attain 3 times the wind velocity does the windmill begin to have a working capacity. The greatest effect is obtained between 5 and 6 times the wind speed.

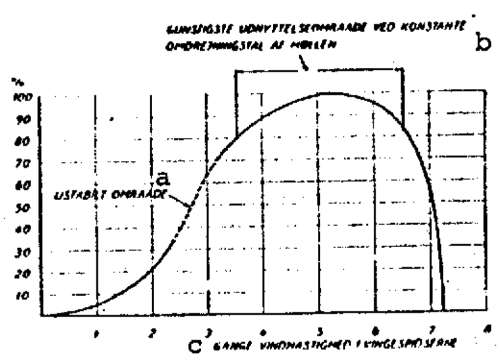

Fig. 9.
Obtainable effect of a two-bladed windmill with streamlined blades for variable tip speed in relation to wind speed.

Key: a. Unstable region; b. Most favorable utilization region for constant rpm; c. Number of times tip speed is greater than wind speed

If an asynchronous generator is coupled to this windmill in such a manner that the frequency value is obtained when the tip speed is 6.5 times the wind speed for 6 m wind, which is the lowest wind force that can be profitably utilized, the generator will keep the windmill's rpm constant so long as it is allowed to furnish the necessary power to load the windmill. The generator must then be dimensioned in such a manner that it is able to do so until the windmill's automatic devices begin to operate and prevent overloading of the generator.

In general it will be most profitable so to dimension it that this point will be reached with a 10-11 m wind because wind forces so seldom exceed this value that it would not pay to build windmills and generators heavy enough to harness greater wind forces.

In this manner the windmill will get its most favorable tip speed, namely, 5-6 times the wind speed, with the most frequently occurring winds that have a working capacity of any importance.

Only experimentation and careful study will reveal what windmill size yields the most power for the least possible consumption of materials.

According to foreign and domestic experience, windmills with /148 an 18-24 m sail and an output of 50-100 kW for a 10 m wind seem, as was mentioned before, to be the most profitable under the wind conditions existing in Denmark.

Such a windmill must meet the following requirements:

1. stormproofness.

2. completely automatic operation, so that its daily operation can be accomplished with local unskilled supervision.

3. it must be so built that it automatically goes into operation with a suitable wind and automatically connects and disconnects, without causing disturbing voltage variations in the local distribution system.

Meeting these requirements will certainly not give rise to great technological difficulties. Such windmills will have no different effect on the existing distribution system than the consumption of equivalent power but with opposite sign, and in sufficient numbers they will be able to produce an estimated 70% of Denmark's electricity consumption at a price on the same order of magnitude as that which it costs to harness wind power by new windmills in our neighboring countries.

Windmills in the necessary numbers will ensure Denmark's electricity supply especially in the event of critical times, such as we have lived through twice in one generation. Apart from this, there will be many other good reasons for setting to work on the task. Our wind conditions here in Denmark and our experience with building windmills and operating wind-driven electricity generating plants can win us a prominent position in this field and create great opportunities for Danish labor.

Owing to the course of events, Professor La Cour's work on the national experimental windmill in Askov did not lead to the desired result at first, but his work did bring it about that agriculture in Denmark was electrified 10 years before it happened in other countries, and that was the beginning of the supply system that now stretches over the entire country and opens up the prospect of reconsidering La Cour's thinking in the light of the latest developments in the field of aerodynamics.

The coming years will bring a great extension of our electricity supply, and in this connection the utilization of wind power must be made the object of thorough andunbiased study by competent institutions and organizations.

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